



LHC combination efforts: ATLAS + CMS

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On behalf of the ATLAS and CMS Collaborations

Outline

- ATLAS+CMS combination of the inclusive and differential charge asymmetry (7 & 8 TeV)
- Towards the legacy Run 1 top mass combination
- New summary plots

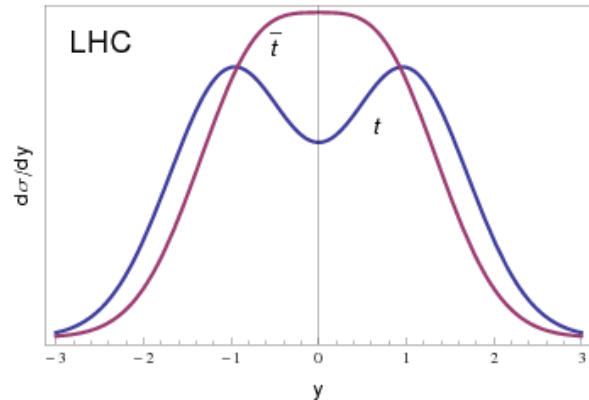
Combination of inclusive and differential $\bar{t}t$ charge asymmetry measurements using ATLAS and CMS data at $\sqrt{s} = 7$ and 8 TeV

arXiv:1709.05327

What is the Charge Asymmetry?

- In proton-proton collisions: asymmetry appears as a central-forward asymmetry
 - Quarks carry more momentum than anti-quarks -> top quark distribution broader than anti-top

• Definition
$$A_C = \frac{N^{\Delta|y|>0} - N^{\Delta|y|<0}}{N^{\Delta|y|>0} + N^{\Delta|y|<0}}$$



See talks by Frederic Derue (ATLAS) & Michele Gallinaro (CMS)

- Where
$$\Delta|y| = |y_t| - |y_{\bar{t}}|$$
- Best theoretical predictions
 - NLO (QCD) + NLO (EWK) [PRD 66 (2012) 034026]
 - NNLO (QCD) + NLO (EWK) [based on arXiv:1705.04105, JHEP 04 (2017) 071, JHEP 05 (2016) 034]

Inclusive A_C		Centre-of-mass energy	
		7 TeV	8 TeV
Theoretical predictions	QCD NLO + EW NLO [3]	0.0115 ± 0.0006	0.0102 ± 0.0005
	QCD NLO + EW NLO [18]	0.0123 ± 0.0005	0.0111 ± 0.0004
	QCD NNLO + EW NLO [19,22,23]		$0.0095^{+0.0005}_{-0.0007}$

Input Measurements

- Both: l+jets channel; fully reconstruct ttbar system
- ATLAS inclusive (7 & 8 TeV) and differential (8 TeV)
 - Correct $|\Delta y|$ distribution to parton level using Fully Bayesian Unfolding (FBU)
 - Subtleties
 - 7 TeV: results for stat and sys uncertainties used before marginalisation
 - 8 TeV: expected uncertainties after marginalisation are used: each systematic is evaluated by building pseudo-data with variations of the predictions and repeating the unfolding procedure
- CMS
 - Unfolding method (7 and 8 TeV differential): unfolds distributions to parton level with Tikhonov-based regularised matrix inversion
 - Template method (8 TeV inclusive): fitting the reconstructed distributions with templates for symmetric and anti-symmetric components; variable used in fit $Y_{t\bar{t}} = \tanh \Delta|y|$

Inclusive A_C		Centre-of-mass energy	
		7 TeV	8 TeV
Experimental results	ATLAS [8,24]	0.006 ± 0.010	0.0090 ± 0.0051
	CMS unfolding [25,26]	$0.004 \pm 0.010 \pm 0.011$	$0.0010 \pm 0.0068 \pm 0.0037$
	CMS template [11]		$0.0033 \pm 0.0026 \pm 0.0033$

Combinations done

- 7 TeV inclusive
- 8 TeV inclusive (using CMS template method)
- 8 TeV differential in $m_{t\bar{t}}$ (using CMS unfolding method)
 - Binning was agreed upon by both experiments before the results were made public
- Side comment: Different methods for estimating uncertainties
 - ATLAS: pseudo-experiments with ‘shifted’ inputs, fit/unfold with default method
 - CMS: repeat fit to data using ‘shifted’ inputs

Combination: BLUE

- All combinations done with BLUE (Best Linear Unbiased Estimate)
 - **Best:** the combined result for the observable obtained this way has the smallest variance
 - i.e. minimising total uncertainty
 - **Linear:** the result is a linear combination of the individual estimates
 - $\text{Combi} = w A + (1-w) C$;
 - **Unbiased Estimate:** when the procedure is repeated for a large number of cases consistent with the underlying multi-dimensional pdf, the mean of all combined results equals the true value of the observable
- BLUE is essentially a χ^2 minimisation with variable weights from each measurement
 - For 2 measurements

$$w = \frac{1 - \rho z}{1 - 2\rho z + z^2}$$

ρ is the correlation

z is the ratio of uncertainties

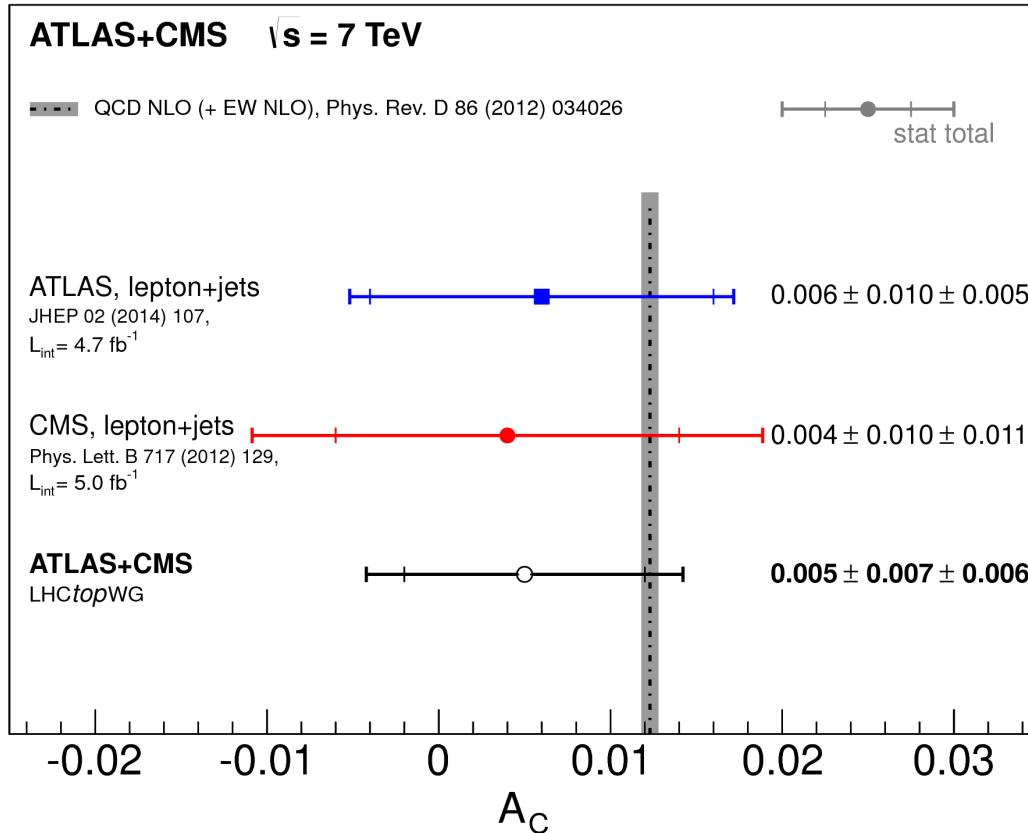
- Assumptions must be made on correlations between ATLAS and CMS for each uncertainty source
- Variations on assumptions considered in stability tests of the combination

7 TeV Inclusive: Systematics

- Coarser model used as older results and less breakdown available / less harmonisation between experiments
 - e.g. all detector related uncertainties as single uncertainty, treated as uncorrelated (despite some b-jet and jet uncertainties known to be somewhat correlated)

	ATLAS	CMS	ρ	Combined	
A_C	0.006	0.004	0.058	0.005	
Statistical (data)	0.010	0.010	0	0.007	←
Statistical (simulation)	0.002	0.002	0	0.001	
Detector model	0.004	0.007	0	0.004	←
Pile-up+ p_T^{miss}	0.002	< 0.001	0	0.001	
Signal modelling	< 0.001	0.002	0.5	0.001	
PDF	0.001	0.002	1	0.001	
Multijet	< 0.001	0.001	0	0.000	
W +jets	0.002	0.004	0.5	0.003	←
Model dependence					
Specific physics models	< 0.001	—	—	0.000	
General simplified models	—	0.007	—	0.002	
Systematic uncertainty	0.005	0.011		0.006	
Total uncertainty	0.011	0.015		0.009	

7 TeV Inclusive Combination

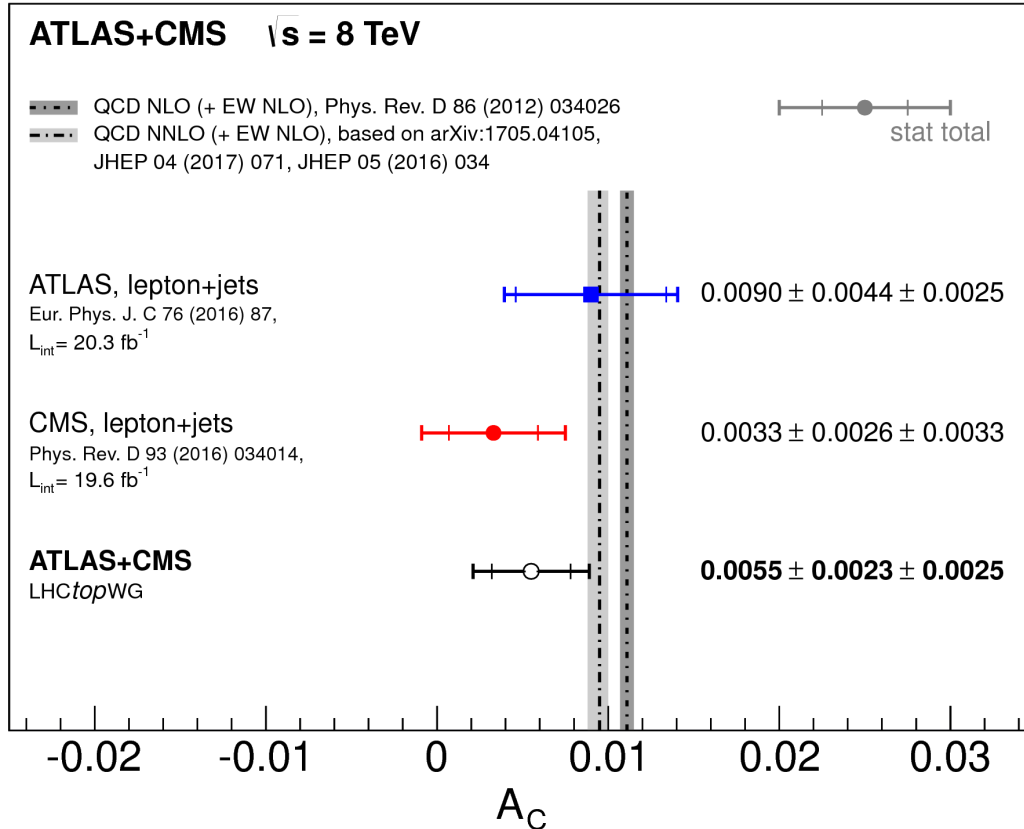


- 18% improvement over ATLAS alone
 - ATLAS weight 0.65
- 40% improvement over CMS alone
 - CMS weight 0.35

8 TeV Inclusive: Systematics

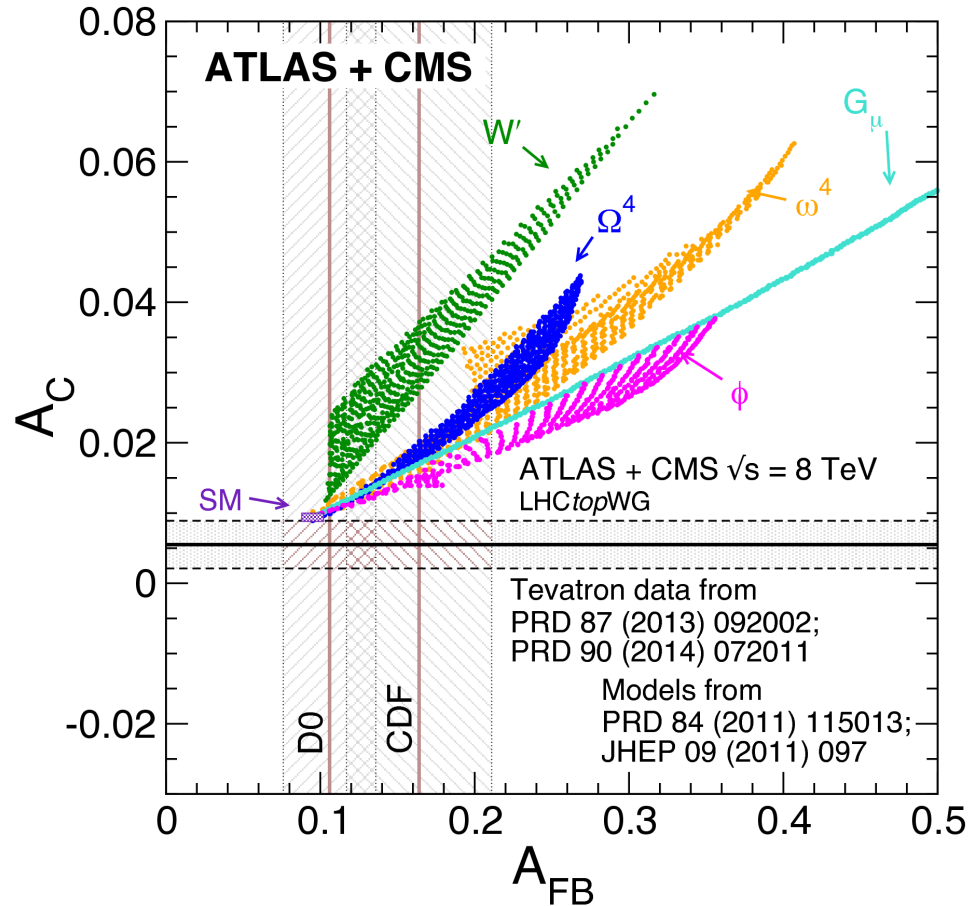
	ATLAS	CMS	ρ	Combined	
A_C	0.0090	0.0033	0.13	0.0055	
Statistical (data)	0.0044	0.0026	0	0.0023	←
Statistical (simulation)	0.0010	0.0015	0	0.0010	←
<i>Detector model (excluding JES)</i>					
Leptons	0.0003	0.0001	0	0.0001	
Jet energy resolution	0.0005	0.0004	0	0.0003	
b -tagging	0.0004	0.0007	0	0.0005	
Missing transverse momentum	0.0002	—	—	0.0001	
Pile-up	—	0.0003	—	0.0002	
<i>Jet energy scale</i>					
Uncorrelated JES	0.0010	0.0004	0	0.0005	
Partially correlated JES	0.0009	0.0010	0.5	0.0008	←
Mostly correlated JES	0.0002	0.0004	1	0.0003	
Fully correlated JES	0.0009	0.0008	1	0.0008	←
<i>Signal modelling</i>					
Event generator	0.0004	0.0002	1	0.0003	
Parton shower and hadronisation	0.0004	—	—	0.0002	
Scale/radiation	0.0009	0.0014	1	0.0012	←
PDF	0.0007	0.0002	1	0.0004	
Integrated luminosity	—	0.0001	—	0.0001	
<i>Backgrounds</i>					
Single-top-quark / Z +jets	0.0001	0.0004	1	0.0003	
Multijet	0.0005	0.0018	0	0.0011	←
W +jets	—	0.0002	—	0.0001	
Method	0.0003	—	—	0.0001	
Systematic uncertainty	0.0025	0.0033		0.0025	
Total uncertainty	0.0051	0.0041		0.0034	

8 TeV Inclusive Combination



- 32% improvement over ATLAS alone
 - ATLAS weight 0.39
- 17% improvement over CMS alone
 - CMS weight 0.61

8 TeV Inclusive Combination



8 TeV Differential: Correlation

- Use same systematics mapping as inclusive
- Now have bin-to-bin correlations for a particular source
- How to deal with correlation between bins?
- Statistical: from unfolding
- Systematics: correlation of source u between bins i and j
 - Within CMS
 - $\text{corr}_u(C_i, C_j) = \text{sign}[(A_C^u(C_i) - A_C^{\text{nom}}(C_i)) (A_C^u(C_j) - A_C^{\text{nom}}(C_j))]$
 - +1 or -1 for each source
 - Within ATLAS
 - Projection of posterior prob denstiy into the (i,j) plane
 - And: +1 or -1 for non-marginalised systematics
 - Cross-check: +1 or -1 for all systematics

1	C_{12}	C_{13}	C_{14}	C_{15}	C_{16}
C_{12}	1	C_{23}	C_{24}		
C_{13}	C_{23}	1	C_{34}		
C_{14}	C_{24}	C_{34}	1		
C_{15}				1	
C_{16}					1

1	A_{12}	A_{13}	A_{14}	A_{15}	A_{16}
A_{12}	1	A_{23}	A_{24}		
A_{13}	A_{23}	1	A_{34}		
A_{14}	A_{24}	A_{34}	1		
A_{15}				1	
A_{16}					1

8 TeV Differential: Correlations

- Correlations between ATLAS and CMS
 - For the same bin: as for inclusive measurement (ρ_u)
 - Between bins: average between ATLAS and CMS

$$\text{corr}_u(A_i, C_j) = \rho_u \cdot \frac{\text{corr}_u(C_i, C_j) + \text{corr}_u(A_i, A_j)}{2}$$

- Cross-check: use only ATLAS or only CMS inter-bin correlation assumption

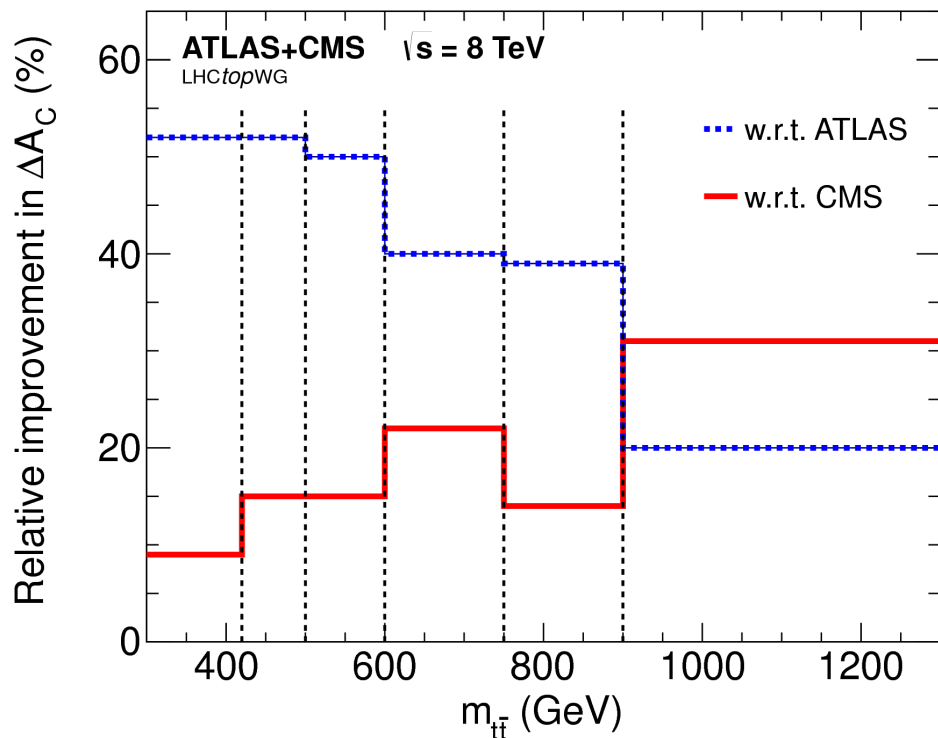
ATLAS bins

	A1	A2	A3	A4	A5	A6
C1	ρ	ρ_{12}	ρ_{13}	ρ_{14}	ρ_{15}	ρ_{16}
C2	ρ_{12}	ρ	ρ_{23}	ρ_{24}		
C3	ρ_{13}	ρ_{23}	ρ	ρ_{34}		
C4	ρ_{14}	ρ_{24}	ρ_{34}	ρ		
C5	ρ_{15}				ρ	
C6	ρ_{16}					ρ



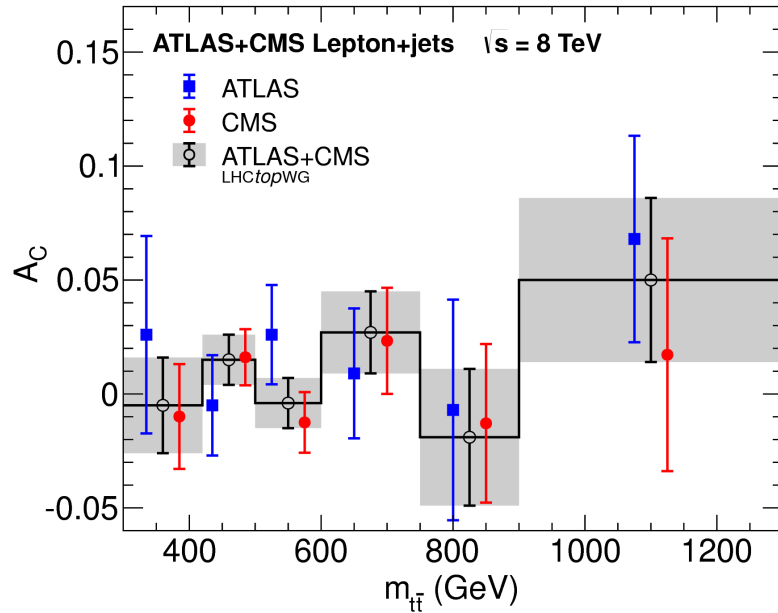
	ATLAS bins 1-6						CMS bins 1-6					
ATLAS bins 1-6	1	A ₁₂	A ₁₃	A ₁₄	A ₁₅	A ₁₆	ρ	ρ_{12}	ρ_{13}	ρ_{14}	ρ_{15}	ρ_{16}
	A ₁₂	1	A ₂₃	A ₂₄			ρ_{12}	ρ	ρ_{23}	ρ_{24}		
	A ₁₃	A ₂₃	1	A ₃₄			ρ_{13}	ρ_{23}	ρ	ρ_{34}		
	A ₁₄	A ₂₄	A ₃₄	1			ρ_{14}	ρ_{24}	ρ_{34}	ρ		
	A ₁₅				1		ρ_{15}				ρ	
	A ₁₆					1	ρ_{16}					ρ
CMS bins 1-6	ρ	ρ_{12}	ρ_{13}	ρ_{14}	ρ_{15}	ρ_{16}	1	C ₁₂	C ₁₃	C ₁₄	C ₁₅	C ₁₆
	ρ_{12}	ρ	ρ_{23}	ρ_{24}			C ₁₂	1	C ₂₃	C ₂₄		
	ρ_{13}	ρ_{23}	ρ	ρ_{34}			C ₁₃	C ₂₃	1	C ₃₄		
	ρ_{14}	ρ_{24}	ρ_{34}	ρ			C ₁₄	C ₂₄	C ₃₄	1		
	ρ_{15}				ρ		C ₁₅				1	
	ρ_{16}					ρ	C ₁₆					1

8 TeV Differential: Relative improvement in uncertainty

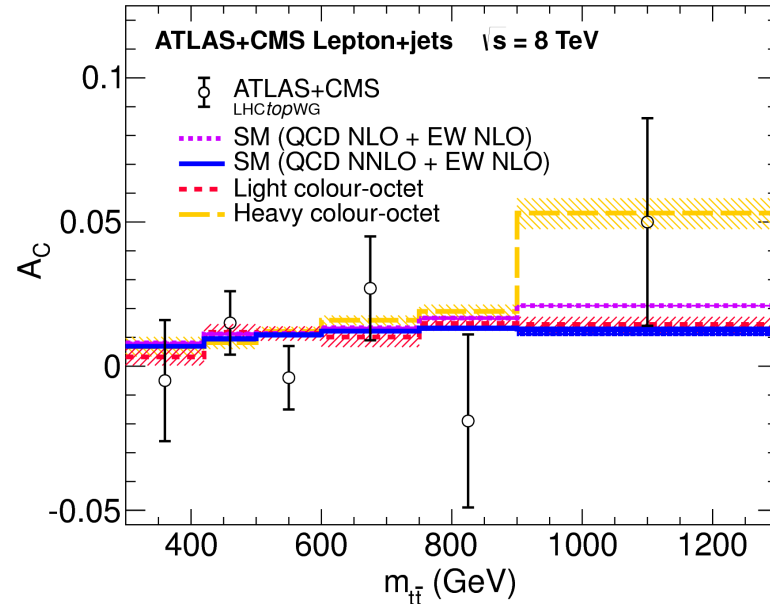


- 20% (last bin) to 52% (first bin) improvement over ATLAS result
 - Weight: 0.22 (first bin) to 0.59 (last bin)
- 9% (first bin) to 31% (last bin) improvement over CMS result
 - Weight: 0.41 (last bin) to 0.78 (first bin)

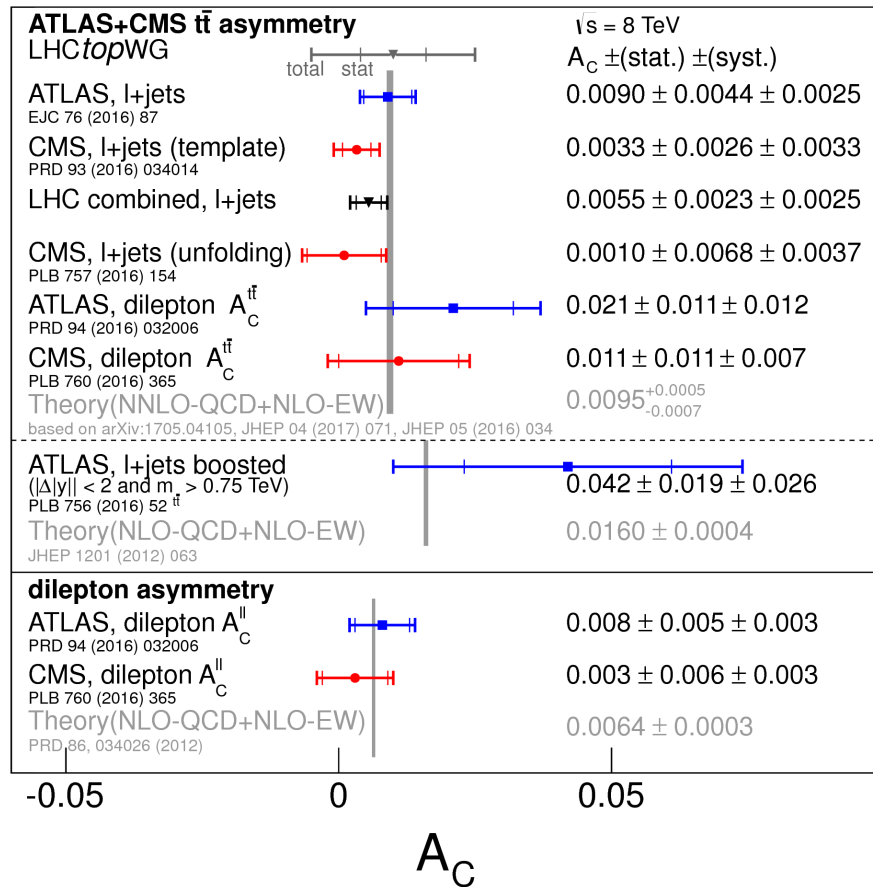
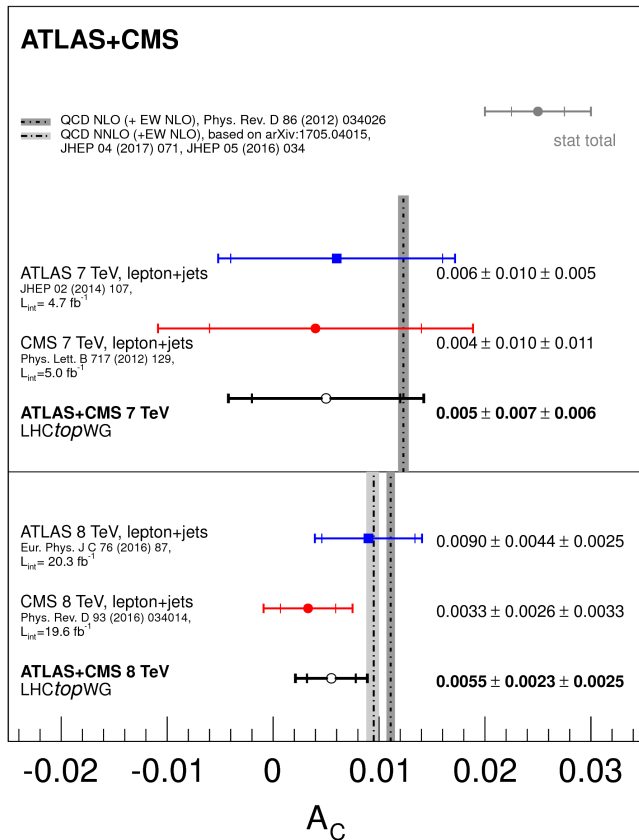
8 TeV Differential Combination



Special thanks to our
theory friends for
producing the NNLO
calculations for us



CA Summary



Towards a legacy Run 1 top mass measurement

Goals

- Publication of the combination of Run 1 top mass measurements (MC mass)
- Legacy measurement from the LHC
- Hope to be quoted in PDG and used for future world combinations
- Use only published results
- Start with ‘standard’ measurements in each channel from both experiments, add in others if might help and when correlations sufficiently well understood

‘Standard’ Measurements

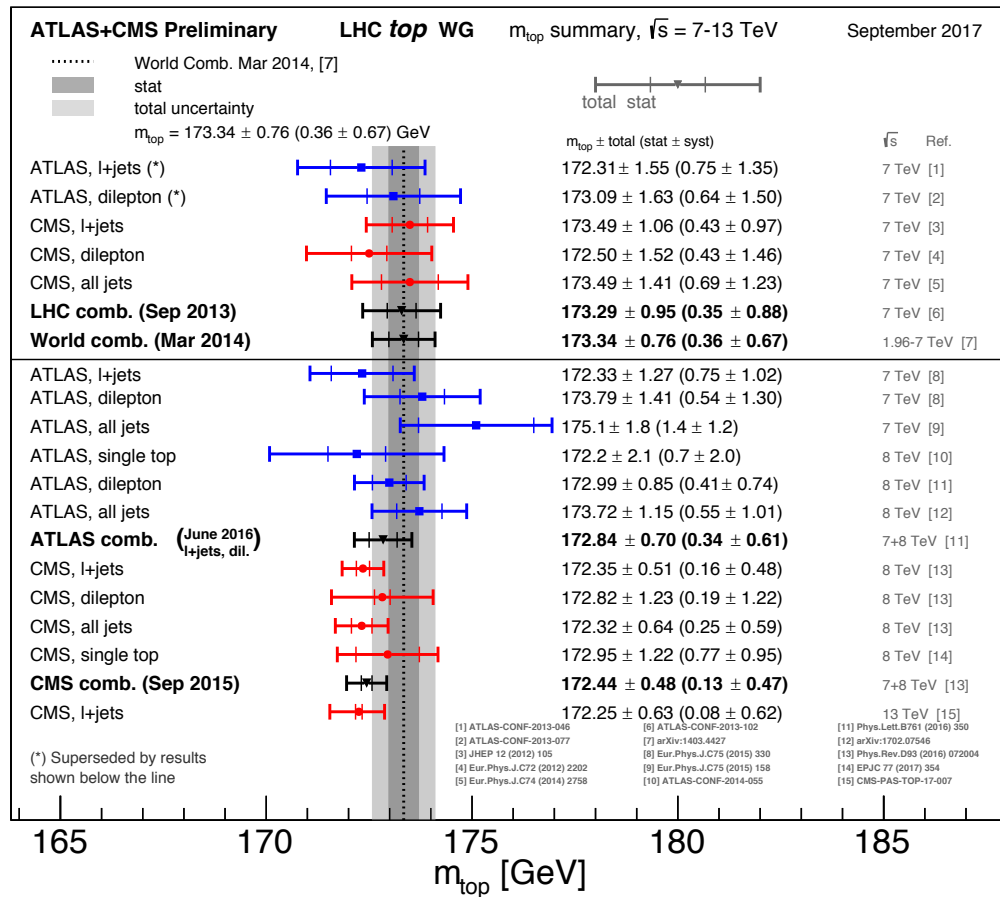
- CMS
 - 7 TeV
 - l+jets, dilepton (AMWT 1D) and all jets [PRD 93 (2016) 072004]
 - 8 TeV
 - hybrid l+jets, dilepton (AMWT 1D) and hybrid all jets[PRD 93 (2016) 072004]
- ATLAS
 - 7 TeV
 - l+jets, dilepton [EPJC 75 (2015) 330]
 - all-jets [EPJC 75 (2015) 18]
 - 8 TeV
 - dilepton [PL B761 (2016) 350]
 - all-jets [arXiv:1702.07546, accepted by JHEP]
 - l+jets [new for this conference]

Possible Correlation Strategy

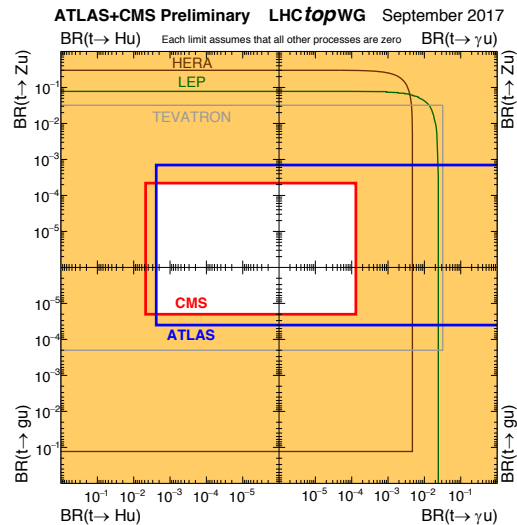
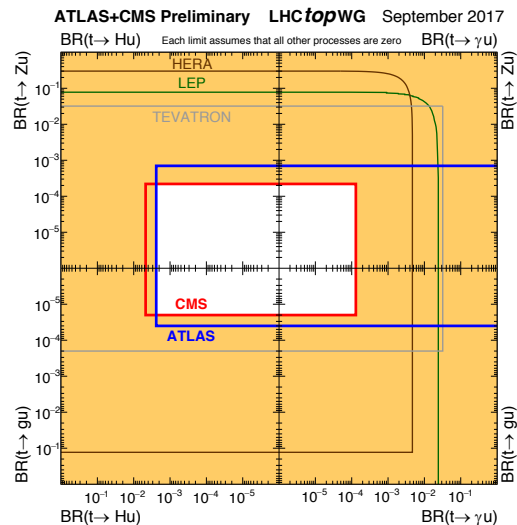
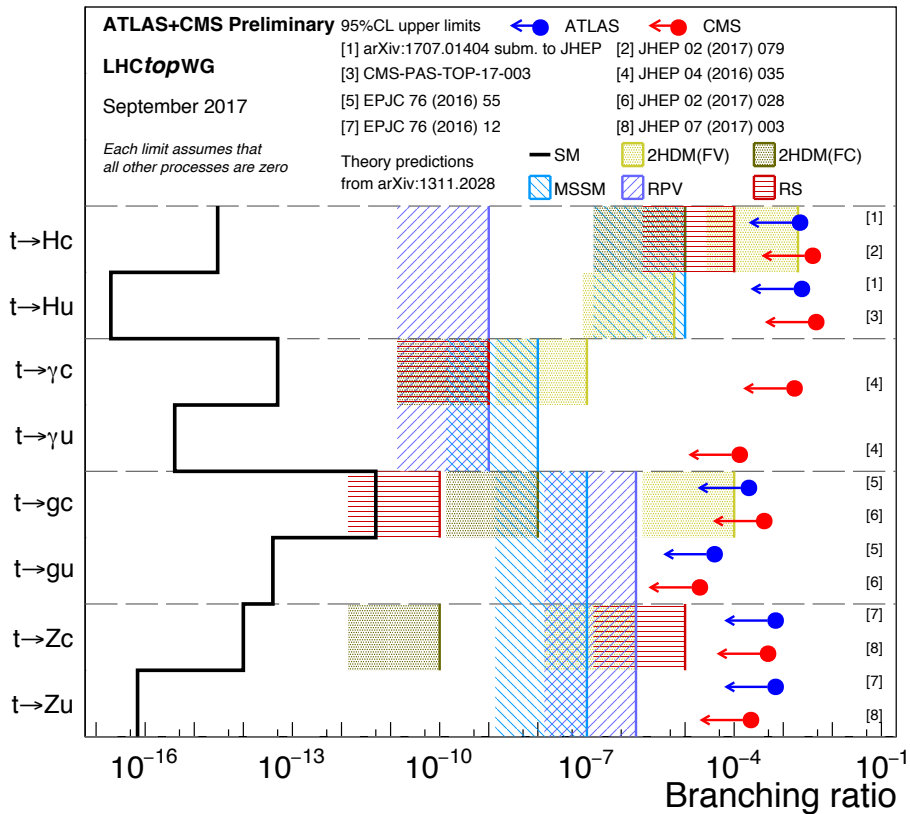
- Intra-experiment correlations already in place (legacy paper for CMS, combinations for ATLAS)
- Work out subtleties needed for inter-experiment correlations
- Detector related uncertainties
 - Most un-correlated between experiments
 - More subtle cases
 - splitting of JES and b-tagging between correlated and un-correlated or taking intermediate correlation terms
- Modelling/generator uncertainties (ISR/FSR, PS, generator,...)
 - Will need some clever matching between terms used in both experiments but derived differently

Other New LHCtopWG Summary Plots

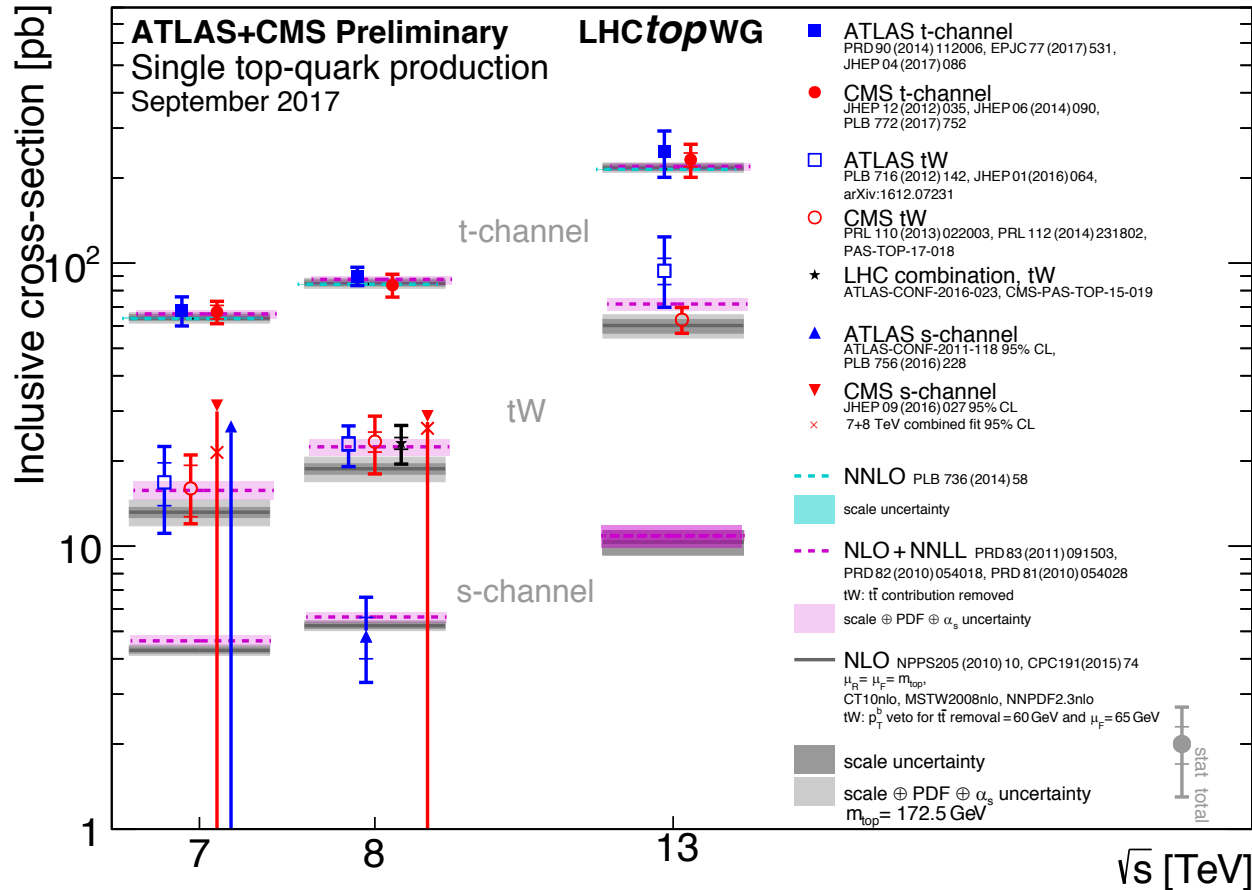
Top Mass



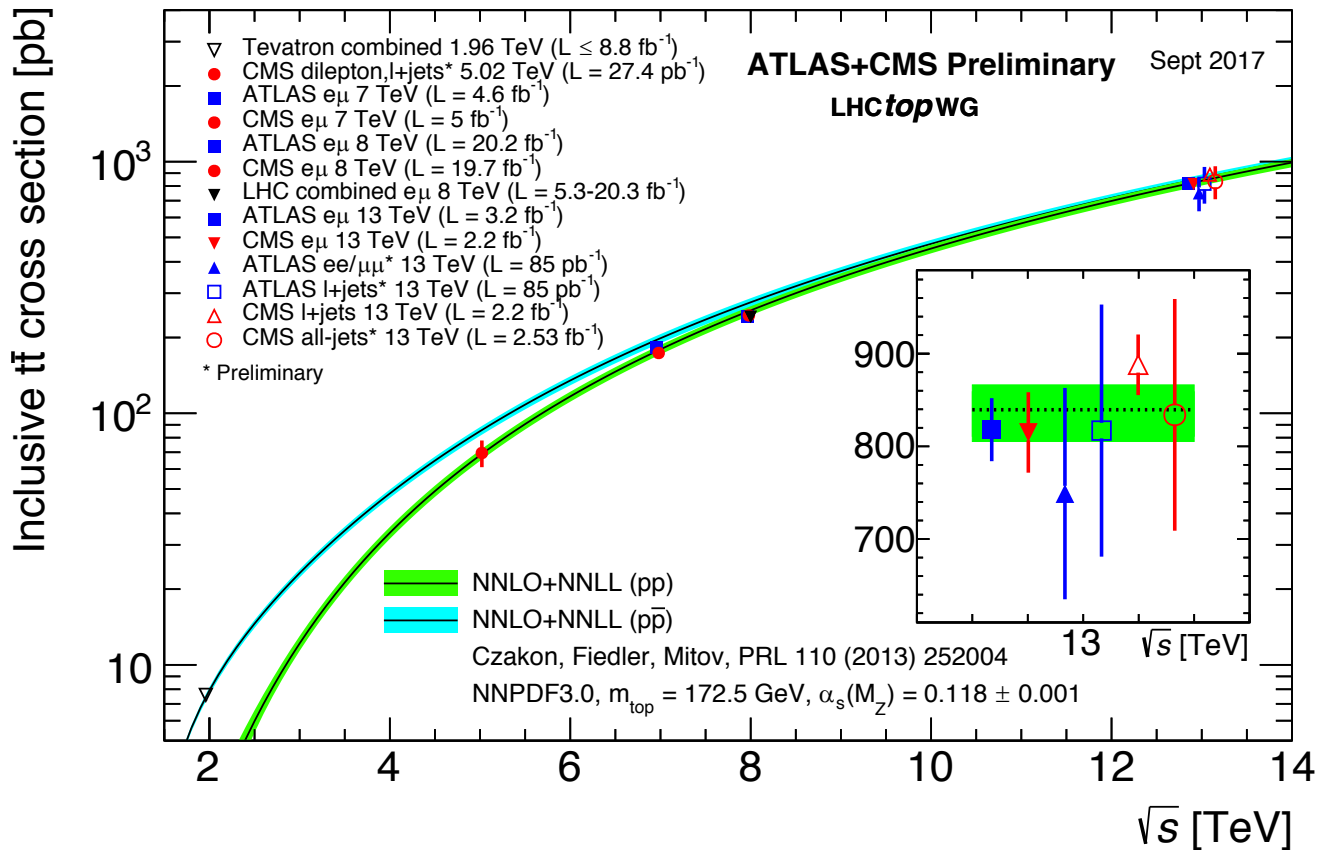
FCNC



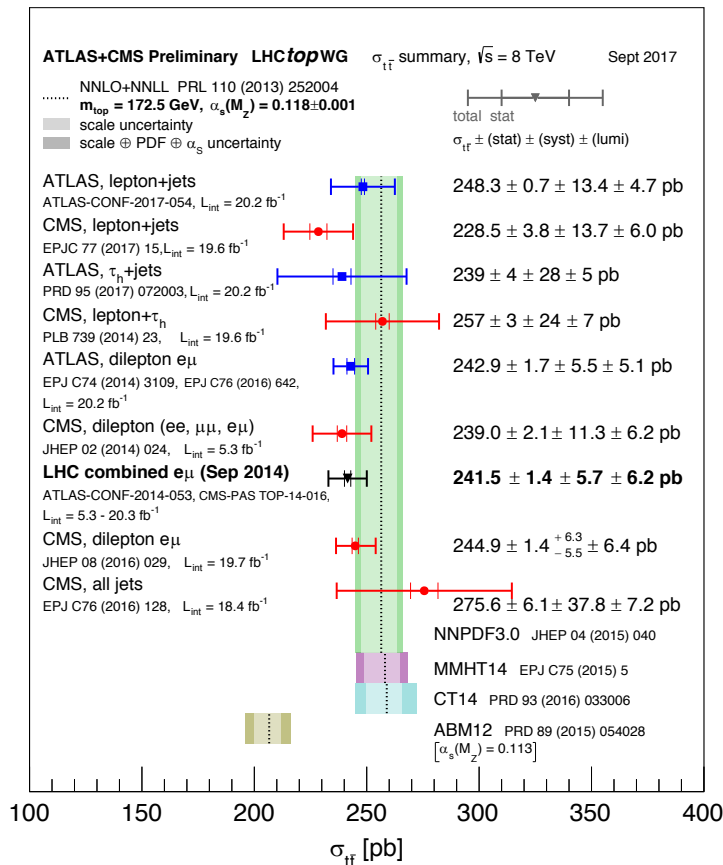
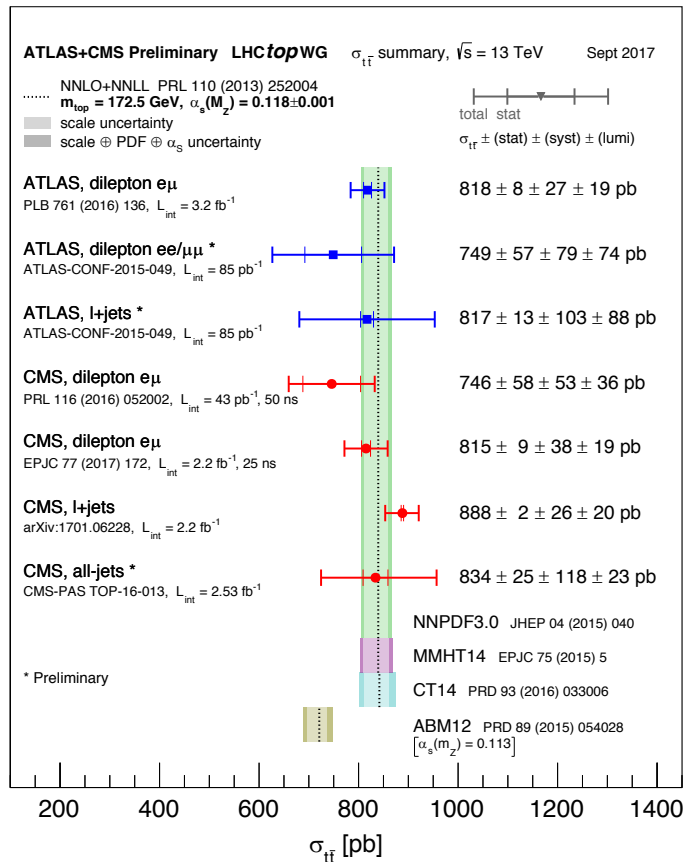
Single top



Ttbar Cross Section



Ttbar Cross Section



Summary and Outlook

- Charge asymmetry combination from Run 1 is first publication of ATLAS+CMS combination from top groups
 - Significant improvement in precision
 - Allows a thorough understanding and scrutiny of the two results
- LHCTopWG now working towards
 - Run 1 legacy top mass combination
 - Run 1 single top Vtb combination
- **Come join in the fun!**
 - Twice yearly LHCTopWG open meetings
 - Lots of exciting discussions, including on top modelling (which wasn't mentioned today)
 - All meetings: <https://indico.cern.ch/category/9219/>
 - Next meeting: **2-3 November**
 - Mailing list: lhc-toplhwcg@cern.ch
 - Regular closed sessions for relevant ATLAS+CMS members to openly discuss plans and work towards these common efforts

Backup

More on Stability Checks

- Method: vary correlations one by one, look at impact on final combined result
- 7 TeV
 - When 100% or 0% was assumed, check with 50% ; W+jets (50%): check both 0% and 100%
 - Impacts all negligible, i.e. $< 10^{-3}$ (quoted precision) on central value
- 8 TeV
 - Removing entirely all systematics impacts total uncertainty by $< 0.5\sigma_{\text{stat}}$
 - All variations of systematic uncertainties won't have big impact
 - Inclusive: no variation $> 10^{-4}$ on central value, negligible impact on uncertainty
 - Differential: impact of changes $< 0.1\sigma_{\text{tot}}$ for all bins
- Additional 8 TeV differential checks
 - Vary assumptions on bin-to-bin correlations within single analysis
 - ATLAS uses correlation from FBU: Change all to +1; all to +1 or -1 (if positive or negative correlation)
 - Impact on all bins: $< 0.4\sigma$ on central value; ≤ 0.002 on uncertainty
 - Change inter-bin-inter-experiment correlations (default) to inter-bin correlations either only from ATLAS or only from CMS
 - Impact: $< 0.3\sigma$ on central value; up to 0.002 increase in uncertainty (ATLAS model)

Test: Parton Shower and Hadronisation

- CMS template analysis doesn't include uncertainty due to modelling of PS and hadronisation
- Estimate impact of this additional uncertainty on inclusive measurement by using value from CMS unfolding analysis (0.0011) scaled up by factor 2
 - Factor 2 from comparing ratio of other modelling uncertainties between 2 analyses
- Impact on measurement
 - Central value increases by 0.016σ
 - Total uncertainty increases by 12%
 - ✓ Small impact

8 TeV Differential Combination

- 9-31% improvement over CMS result
- 20-52% improvement over ATLAS result

	$m_{\ell\ell}$ region (GeV)					
	0 – 420	420 – 500	500 – 600	600 – 750	750 – 900	> 900
ATLAS A_C	0.026	-0.005	0.026	0.009	-0.007	0.068
stat. unc.	0.025	0.017	0.018	0.023	0.042	0.037
syst. unc.	0.036	0.015	0.012	0.017	0.025	0.026
CMS A_C	-0.010	0.016	-0.013	0.023	-0.013	0.017
stat. unc.	0.020	0.011	0.012	0.015	0.026	0.038
syst. unc.	0.012	0.006	0.006	0.018	0.023	0.035
Combined A_C	-0.005	0.015	-0.004	0.027	-0.019	0.050
stat. unc.	0.017	0.009	0.009	0.012	0.022	0.027
syst. unc.	0.013	0.006	0.007	0.014	0.020	0.024
QCD NLO + EW NLO	0.00809	0.01117	0.01138	0.01335	0.01671	0.02100
uncertainty	0.00036	0.00053	0.00039	0.00038	0.00058	0.00025
QCD NNLO + EW NLO	0.00690	0.00950	0.01095	0.01219	0.01327	0.01286
uncertainty	+0.00061	+0.00081	+0.00079	+0.00054	+0.00075	+0.00083
	-0.00058	-0.00087	-0.00095	-0.00081	-0.00101	-0.00231